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Low-Mass Neutron Stars as Anomalous Pulsars

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Abstract. A neutron star with mass close to the lower limit might be a reasonable model for some anomalous pulsars. Emission is thermal. X-ray luminosity is high. Spatial velocity can be high. Since the radius is predicted to be large, the magnetic field calculated for spin-down is lower than that required by the magnetar model.

1. Introduction

Almost every pulsar has precisely measured period, P, and the rate of change of period with time, $\dot{P}$. The gross properties of these objects are well illustrated by the $P - \dot{P}$ diagram which now shows rotational data for ~ 1200 isolated (as far as we know) pulsars. The accepted model, a rotating, strongly magnetized, neutron star, gives a plausible explanation for the behavior and evolution of most of these objects.

Approximately 10 objects, having both large P and $\dot{P}$, form a loose group in the upper right corner. Here the dipole model predicts large values for the magnetic moment, M, and the surface field, B. Indeed, the energy in the predicted magnetic field exceeds the rotational energy in this part of the diagram. These objects are the Anomalous X-ray Pulsars (AXP) and the the Soft Gamma-ray Repeaters (SGR) which we refer to collectively as anomalous pulsars. Also for these pulsars the observed X-ray luminosity also greatly exceeds the rate of loss of rotational energy.

Some anomalous pulsars are associated with supernova remnants, and the short lifetimes indicated by $P/2\dot{P}$ seem appropriate. It has been proposed (Thompson & Duncan 1996) that energy is supplied by decay of the very-strong magnetic field. The interaction of the strong field with the crust of the neutron star is also invoked to explain the γ-ray bursts observed from SGR. AXP/SGRs are also called "magnetars" in the literature. It is assumed that the slowing torque is largely electromagnetic. However, the grouping of anomalous pulsars in the upper right of the $P - \dot{P}$ diagram, suggests that something different is happening rather than an extension of the dipole model. We here explore the possibility that the anomalous pulsars are low-mass neutron stars – objects with mass considerably smaller than the generally-accepted mass of 1.4 $M_\odot$.

2. Neutron Star Structure

In theory, neutron stars can exist having masses between ≈ 0.2 $M_\odot$ and ≈ 3.0 $M_\odot$. The addition of mass at the upper limit causes formation of a black hole. The removal of mass at the lower limit causes nuclei in the crust to fission and
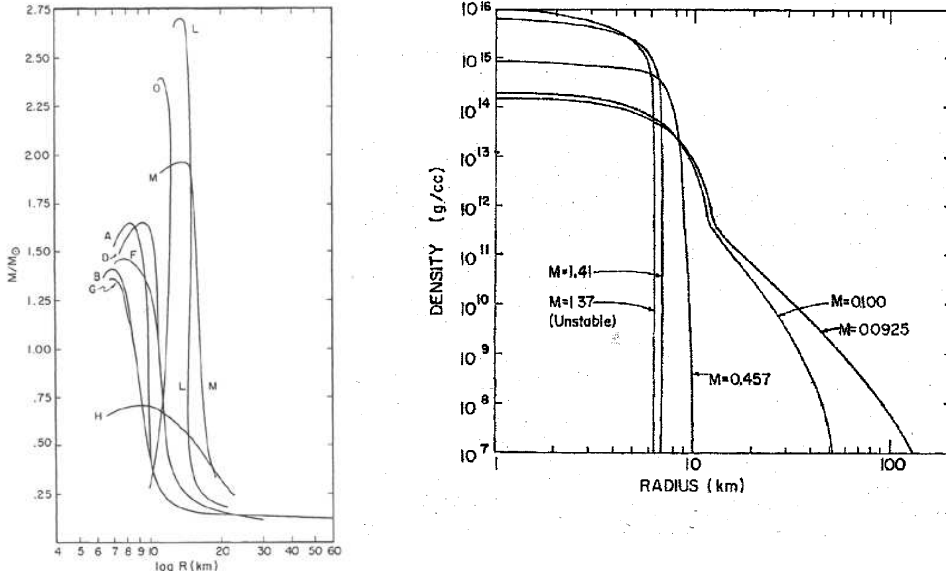
Figure 1.   *(a)Neutron star mass-radius relation for several eq. of state. (b)Density vs radius for neutron stars of different masses.*

beta decay with release of energy and consequent disruption of the star (Colpi, Shapiro, Teukolsky, 1991).

The only mass measurements are for neutron stars in binary systems. The masses of 19 radio pulsars, deduced from measured orbital parameters and characteristics of the companion star are all compatible with a mass of 1.35 ± 0.04 $M_\odot$ (Thorsett & Chakrabarty, 1999), but uncertainty of the measurements for 2 systems allow masses slightly below 1.0 $M_\odot$. The masses of 7 X-ray emitting accretion-powered pulsars in binary systems are all compatible with a mass of 1.4 $M_\odot$, but larger uncertainties allow masses ranging from 0.5 to 2.5 $M_\odot$ (van Kerkwijk et al 1995).

Since gravitational collapse of a massive star in a type II supernova is thought to produce an ≈ 1.4 $M_\odot$ compact object, the general belief is that all neutron stars are so formed and have this mass. Larger masses might be achieved through accretion by neutron stars in binary systems but there is presently no evidence for masses ≤ 1.3 $M_\odot$; so the subject of this paper is speculative.

Neutron star properties, including the lower-mass limit, are dependent on the equation of state which is unknown for the high density at the center of a neutron star. Arnett & Bowers (1977) constructed neutron star models for 15 equations of state (Figure 1a). More recent models are given by Lattimer & Prakash (2000). Lower limits of 0.2 - 0.4 $M_\odot$ are calculated for most models. "Soft" equations of state predict an almost constant radius of between 8 and 15 km (dependent on eq. of state) for masses 0.5-1.4 $M_\odot$. Then, as the mass approaches the lower limit, the radius, R, increases rapidly. A "stiff" equation of state predicts a more linear dependence of radius on mass.

Figure 1b, from Baym et al (1971), shows density profiles calculated using one eq. of state and 5 different masses. The 1.4 $M_\odot$ star has a radius of 7 km, the 0.5 $M_\odot$ star a radius of 10 km, and the 0.1 $M_\odot$ star a radius of 50 km. As a point of interest, the 0.1 $M_\odot$ star is completely solid; there is no liquid core.

3. Cooling

A neutron star formed in a supernova explosion should be born hot and will cool with time. Cooling is dominated by neutrino emission from the core for $\approx 10^4$ years, then by photon emission from the surface. Initially the core cools rapidly and the surface remains hot until the heat is conducted to the core.

Figure 2, taken from Page and Applegate (1992), shows cooling curves calculated for neutron stars of different masses and includes a direct URCA process which cools the core rapidly. Below a certain mass the central density is low enough so that the direct URCA process no longer occurs. The time for the cooling wave to reach the surface increases as the mass decreases because the crust gets thicker.
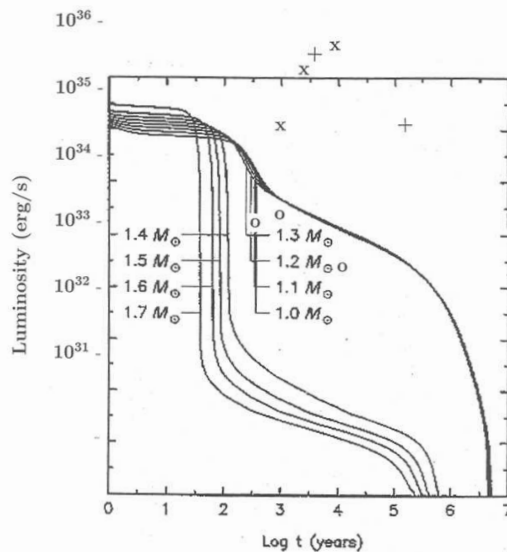

Figure 2. *Luminosity vs time for neutron stars of different masses. Circles below the highest curve show luminosities of 3 young pulsars: the central sources in the remnants: Cas A, 3C 58, and the Vela remnant. Data points above the curve are for 2 AXP and 3 SGR. Ages are uncertain by at least a factor of 2 and distances are not well known except for one SGR in the Large Magellanic cloud.*

If a neutron star has low central density (and consequent low mass), early neutrino cooling will be greatly reduced. There will be no "exotic" cooling processes and the crust will be thick. Even if there is some cooling of the core, the surface will remain hot until cooled by photon emission. The larger radius expected from a low-mass star will also help to achieve a high luminosity. At an age of a few thousand years, the star must have thermal luminosity in excess of 10^{35} erg s^{-1}.

As a matter of interest, if thermal conductivity is greater along the field lines, and if the core cools first, phase-resolved spectra might show cool spots at the magnetic poles - quite different than the hot poles expected from accretion.

4.   Magnetic Field

The spindown rate, $\dot{P}$, of anomalous pulsars is erratic, demonstrating that another process, probably a wind, is responsible for much of the torque (Marsden et al, 1999). Certainly some magnetic field is required to account for the pulsations but characteristic ages calculated using the dipole model (and used to place points in Figure 2) are not expected to be reliable.

One difficulty with the magnetar model is the high value of magnetic field at the surface (eg. 10^{15} Gauss for SGR 1900+14). Equating the loss of rotational energy to the rate of dipole radiation gives a value for the dipole moment, M. Since the external field of a dipole along the axis is $B_p = M/2R^3$, the surface field at the pole can be expressed as:

$$B_p = [3c^3 I P \dot{P}/8\pi^2]^{1/2}[R]^{-3}$$

Given M, a low-mass neutron star with large R will have considerably lower surface field than the usual ($R = 10$ km) model. Also the moment of inertia, I, roughly scales with mass (Arnett & Bowers 1977). If the mass of the model is lowered until $R = 20$ km, the value of B at the surface will decrease a factor of 10. If the radius is 40 km, B will be 100 times less than the usual model. The total energy in the field will also drop factors of 10 and 100 in these 2 examples.

5.   Other Considerations

Some anomalous pulsars are thought to be high-velocity objects. Less energy is required to accelerate a low-mass star than a canonical one. This might be accomplished through asymmetric radiation (Harrison & Tademaru 1975) or during formation.

The process by which low-mass neutron stars may be formed is unknown. Gravitational collapse requires a core of $\sim 1 M_\odot$. The collapse of a rotating system with magnetic field might, in spite of gravitational radiation, produce smaller fragments. It will be difficult, however, to identify a low-mass isolated neutron star with present observational techique. The surface and emission process are not well enough understood to derive the radius from spectral data.

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